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Purpose: Investigator was to test an invention in electron optics that might allow development of a very high-resolution cathode ray tube (CRT) suitable for digital mammography workstations. Scope: The invention solves a very old problem in electron optics and is patented. The invention allows deflection of a wide beam into large angles using electric fields with little or no acquired aberrations. Major findings: This project was successfully completed. The invention worked as predicted and results have been published in Journal Vacuum Science and Technology - B 20(6): 2678-81, Nov/Dec 2002. Results and Significance: While it is now technically possible to develop such a CRT display device, a new flat panel display was announced by IBM that seems to fulfil the mammography application needs. Thus while this project was a technical success, this particular application has been fulfilled by another company's product. We are now looking for other applications where our technology can make a contribution. Fortunately, there are many opportunities ranging from electron beam lithography to isotope separation and mass spectrometry.

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3. M. Retsky and R. Stein. Testing an electron beam deflection innovation: Initial results. Jour. Vacuum Science and Tech. B 20(6): 2678-2681, Nov/Dec 2002.

4. M. Retsky. Very High resolution display for digital mammography workstations. Era of Hope. Dept of the Army Breast Cancer Research Conference. Orlando, FL. Sept 2002,

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Reportable outcomes:
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All the above are discussed in the publications attached in the appendix.

Additional information:
IBM has developed a 9.2 megapixel active matrix liquid crystal display suitable for mammography workstations (Information Display 5&6/2001) so the need for a cathode ray tube solution has been greatly diminished. As a result Electron Optics Development is now looking for other applications of the electrostatic deflection technology. We are concentrating on electron beam lithography, isotope separation, mass spectroscopy and a few other applications.

References and Appendices:

1. M Retsky, Testing an electron beam deflection innovation. SPIE The International Society for Optical Engineering, Charged Particle Optics, San Diego May 2001.

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Testing an electron beam deflection innovation

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ABSTRACT

While not obvious, deflection aberration is a key aberration in Cathode Ray Tube (CRT) design. A new concept in electron beam deflection with electric fields, originally proposed in 1997, is now being tested in the laboratory. Using a beam injected off the axis of symmetry, deflection aberrations are predicted to be 10 fold reduced compared to symmetrical injection. This would be less than magnetic deflection aberrations. If the invention proves to be valid, important improvements are possible in CRT brightness, resolution, energy consumption, and footprint reduction. As one example, reducing deflection aberrations allows larger beam diameters in the deflection plane as well as larger deflection angles. This will reduce space charge spread, allowing larger beam currents and/or smaller focussed spot size. Improved medical imaging displays could be built. For another example, much of the energy consumed in a magnetically deflected CRT display is associated with deflection. Electric deflection has a significant advantage in energy consumed compared to magnetic deflection. With 400 million CRTs in daily use in the US consuming 0.54 quads, there is a large incentive to reduce power consumption in CRTs particularly so since excess heat produced adds to office air conditioning loads.

Keywords: Electric deflection aberration CRT energy consumption mammography workstation display

1. INTRODUCTION

In a CRT, an electron beam is scanned in raster fashion over a phosphor screen. The current in the beam is modulated to produce the desired light output pattern. Because of the low mass of electrons it is easy to deflect electron beams. It is much harder to additionally preserve the ability to finely focus the beam after deflection. Since deflection aberrations increase with beam diameter and angle of deflection, a variety of interrelated detrimental attributes of CRTs such as large footprint and limited resolution are ultimately traceable to design compromises stemming from deflection aberrations.

There are two ways to deflect an electron beam - using magnetic fields or electric fields. The vast majority of CRT displays use magnetic deflection. The basic advantage of magnetic deflection is that deflection aberrations are lower by a factor of 2 or 3 compared to electric field deflection.[1-3] However, electric (often called electrostatic whether the activity is static or dynamic) deflection is more energy efficient. According to Tsukkerman,[2] for a beam voltage of 20 kV, electric field deflection requires only 26% as much energy as magnetic field deflection. While magnetic deflection is better for aberrations, electrostatic deflection is better for energy efficiency. A way to significantly reduce electrostatic deflection aberrations would be an important development.

This has recently been accomplished - at least according to calculations. A new method has been invented for electrostatic deflection, which for the first time makes electric field deflection aberrations lower than for magnetic field deflection. The invention has been patented and published.[4-6] In brief, when using electrostatic deflection, electrons are directed to pass between oppositely charged shaped conducting plates. It has always been assumed that the optimum injection placement of the beam is symmetrically between the deflection plates. I have found that, instead, electrostatic deflection aberrations can be reduced 10 fold by injecting the electron beam at an optimized offset position into a conventional deflection plate assembly. The "sweet spot" is not near the center where it would be expected based upon looking at the fringe fields (fig. 1). The optimum injection position is far offset towards the attracting plate. US patent 5,825,123 was issued Oct 20, 1998 and 6,232,709 was issued May 15, 2001 for this invention. The computed improvement in deflection aberration with offset is seen in fig. 2. If conventionally injected in the center between the two shaped deflection plates the best focused beam has 0.004" diameter. At optimum injection offset the beam focuses down to 0.00025" - a 16 fold reduction. The optimum offset is 33% toward the attracting plate in this example.

The concept of solving an electron optics problem using asymmetry is not new. In Feynman's famous 1959 talk to the American Physical Society at CalTech when nanotechnology was first mentioned, he lamented the limited resolution of

electron microscopes: "The reason the electron microscope is so poor is that the f value of the lenses is only 1 part to 1000: you do not have a big enough numerical aperture. And I know that there are theorems which prove that it is impossible, with axially symmetrical field lenses, to produce an f value any bigger than so and so; and therefore the resolving power at the present time is at its theoretical maximum. But in every theory there are assumptions. Why must the field be symmetrical? I put this to you as a challenge: Is there no way to make the electron microscope more powerful?"[7]

The standard approach to studying deflection aberrations is to approximate solutions to complex integral equations using polynomial expansions of displacement or angle to third and higher order terms. These higher order calculations are highly complex and typically require equations that fill entire pages. This method breaks down far off axis. Perhaps that is why the asymmetrical solution proposed in 1997 was not discovered previously.

In this paper, I will discuss what could be done if the idea works as predicted and then describe the experimental setup under construction to test the innovation. There are many applications in which electron or ion beams are deflected. The applications discussed here are restricted to CRTs - particularly to make an improved resolution/brightness monochrome CRT for medical imaging and to make a lower energy consuming color CRT with reduced footprint for computer monitors and commercial TV.

2. POTENTIAL RESOLUTION AND BRIGHTNESS ADVANTAGES

In applications of electron optics, it is often desirable to create small, bright focused spots. There is need for such improvements in medical display devices, particularly so when used as the display output of digital mammography workstations. This need is well recognized by National Institutes of Health: "Digital Mammography is one of the most promising research areas for improving early detection of breast cancer; however, current soft-copy (i.e., video) display systems remain an impediment to full realization of the potential of digital mammography. Extensive effort is required for the successful development, testing and implementation of digital mammography displays and workstation design for image interpretation. Studies are needed to objectively evaluate display technologies for mammographic imaging. High resolution display technologies providing high spatial and contrast resolution, high luminance, high dynamic range and wide viewing angle at reasonable cost need to be developed."[8]

There are many factors that can limit the ability to finely focus an electron beam. The more common ones include spherical and chromatic aberrations, magnified source size, misalignments of critical components, mutual coulomb repulsion of the charged particles in the beam, inadequate magnetic and electrostatic shielding, mechanical vibrations, and deflection aberrations. This invention is primarily directed to the correction of deflection aberrations although some of the other aberrations and factors will come into consideration since they are often linked in practical designs.

Electron beam probes having a diameter of a few Angstroms are possible, but only within a very small scanned field of a few hundred Angstroms. Most applications of electron beams, however, require moving the beam around appreciably more. When a beam is deflected, aberrations of deflection are induced. These deflection aberrations are usually significant and often much larger than the undeflected focused spot size.

Researchers have tried to reduce electrostatic deflection aberrations since cathode ray tubes first became useful devices a century ago. While some improvements have been demonstrated over the years, a major solution has yet to be satisfactorily identified.[9-11]

There are two types of image defects that result from deflection. The first is a field defect that distorts rectangles into pincushion or barrel shapes. The second type of defect causes the focused spot to increase in size. The aberrations that cause the focused beam size to increase are of more concern. Depending on the application, an electron beam designer will usually want perimeter or corner resolution to be the same or at least not significantly worse than resolution at the center of focus. Because deflection aberrations are approximately proportional to the beam diameter and the square of the deflection angle, the designer will often compromise center brightness and resolution in order to make corner resolution and brightness acceptable. (Note: Moss reports a linear dependence on beam diameter while I have found a quadratic dependence.) This is typically achieved by reducing the diameter of the beam in the deflection region. As a demonstration of the interdependence among the aberrations, this tends to increase space charge repulsion. That is because space charge spread results from confining too many electrons in too small a volume for too long a time (relatively speaking, of course).

It may seem that the wider beam diameter would increase spherical aberration in the main focus element since the beam

would more fully fill the space within the focus element. However, with electrostatic deflection, the focus elements could be made larger since there is no longer need to slip a small bore deflection yoke over the neck. Small neck diameters are important in magnetic deflection since power consumed by the horizontal deflection circuit is proportional to the volume of space energized by the magnetic field. Large diameter gun focus rings produce lower spherical aberration. A magnetic focus lens (that is possible using electrostatic deflection) has even less spherical aberration.

With all the possible improvements described in this and other sections, the electron optics is probably capable of 20 megapixel resolution – what is considered ideal for the mammography application.[12] This is beyond the current capability of drive electronics. The initial intention is to develop an 8 megapixel, 300 microamp beam current medical display. That beam current allows the use of darker faceplate glass that will improve the display contrast in high ambient lighting and will produce a few additional discernable gray scales. This is within the range of electronics and would be an improvement over what is available today. Marketing input is that this would be well received by customers. There is a modest size market for such a display in a wide variety of medical applications if the product can be sold at or below $5,000.

3. POTENTIAL ENERGY SAVINGS

Cathode ray tube technology was developed at a time when energy was cheap and only considered to be an economic factor - not an environmental factor. As a result, design decisions were made that probably would not have been made today. There are 94.74 million US households with an average 2.28 TVs (A.C. Nielson) and there are approximately 150 million CRTs used as personal computer monitors (Stanford Resources, Inc.). Thus there are approximately 400 million CRT displays in daily use in this country. Typical power consumption is 150 watts. The average usage of a residential TV is 7.25 hours per day. Assuming that the secondary TVs are on 2 hours per day, half of the PCs are on 24 hours per day and the other half are on 2 hours/day, this adds up to 0.54 Quads (end use) for the US. This power is consumed in buildings adding costs and consuming energy - then the additional heat must be pumped out by air conditioners. Thus we pay twice for energy inefficiency of computers and peripherals; at least when air conditioning is used. A significant fraction of the heat load of a well-insulated building is generated internally. Obviously, this cannot be reduced by improved insulation.

To make an inexpensive and energy efficient color display, we are considering to use the old single gun beam index technology or something similar. Patents have long ago expired for the beam index concept that does not employ a shadow mask. (Used in a conventional three electron gun color CRT, the shadow mask is a contoured sheet of metal with many small holes supported just in front of the phosphor screen so that, by parallax, electrons from the red electron gun impinge only upon the red phosphor, etc.) Since it distorts when heated, producing color shifts, the mask is the brightness-limiting element in modern displays. The screen in a beam index CRT is composed of alternating vertical red, green and blue phosphor stripes (applied as a one step decal or using a jet printer). Typically, an ultraviolet phosphor is added to the blue phosphor or is printed on top of the aluminum film reflector over the blue phosphor stripe. An inexpensive internal UV pickup device senses where the beam is relative to the color stripes in real time. While the beam is scanned horizontally, beam intensity is modulated according to chroma and luminance signals to produce the needed hue and intensity. This color CRT is relatively insensitive to changes in external magnetic fields and obviously does not need degaussing coils or degaussing circuitry.

The historic reason why the shadow mask was used instead of the beam index is electron optical in nature. Beam diameters need to be small (less than one phosphor stripe wide) over the entire screen or else the index registration signal is corrupted. With large beam landings in the corners it is difficult to know where the beam is relative to the various color stripes. Beam diameter growth in the corners is a particular problem in CRTs as one might suspect.

But this is the strength of the new invention. Our product would have higher brightness and resolution, perhaps lower cost (deflection yoke and shadow mask are expensive components), weigh the same or less (some additional small parts but again no yoke or shadow mask), smaller footprint, and consume less power than existing products. Our goal is to meet or exceed performance of the Sony G200 FD Trinitron 17" or equivalent display and to do this while using 25% less power. The G200 FD uses a shadow mask grill with 0.24 to 0.25 mm pitch. It can provide resolution of up to 1600 by 1200 at 75 Hz although the recommended operation is 1024 by 768 at 85 Hz. It is 16.5" deep and is specified to consume less than 120 watts.

What would be the energy savings? Ignoring the few watt savings from two fewer cathode heating filaments, a shadow mask intercepts 80% of the electron beam current and wastes it as heat. Since shadow mask color CRTs are operated at 30 kV and 1 ma, eliminating the shadow mask could save 24 watts.

What additionally can be saved from the deflection circuitry? Several questions arise when comparing the circuitry associated energy efficiency of each of these two CRT types. First, what part of the 150 watts consumed by a television receiver might be reducible with a switch to electrostatic deflection from magnetic deflection? It would be confined to that fraction of the 150 watts that is devoted to generating and controlling the horizontal sweep currents - since that is where most of the deflection power is consumed. The currents flow through an external component (yoke) that contains inductive windings on a ferrite core. The second question: What is the power consumption in the horizontal sweep section of a television receiver? Consultant Vernon Beck was asked to review this situation.

Dr. Beck reported that TV receivers set up a magnetic field of average energy 600 volt-amps to deflect the electron beam. This field repeatedly collapses and is reestablished at the sweep frequency of 15.75 kHz. This energy is not lost but is recaptured in large measure by charging a capacitor that will be discharged to power the next cycle. Controlling this power is done at the energy cost of 8% of the average power. This inefficiency amounts to 50 watts, a reasonable overhead level. The losses should increase in the near future as promised higher resolution displays (with more horizontal lines per frame) come on the market.

Since the deflection field energy needed to deflect the beam using electric fields is 26% of the magnetic case, what might be the actual savings in an electrostatically deflected CRT receiver? The deflection field would be 26% of 600 watts or 156 watts. Would the inefficiency of a relatively high voltage sweep circuit be different compared to a magnetic sweep circuit? According to Beck it depends on how the high voltage is generated. If stacking high voltage transistors produces the high voltage, then the inefficiency could be the same or lower. On the other hand if transformers are used to generate the high voltage, then currents are generated and there are attendant heat losses. To conservatively estimate the power consumption of an electrostatic deflection CRT display, the inefficiency of the horizontal sweeps will be taken as 150% of the inefficiency of the magnetic deflection displays or 12%. The resulting calculated power would be.12 * .26 * 600 or 19 watts, or a net savings of 31 watts from switching to more energy efficient electric deflection.

Adding the 31 watt savings (from deflection efficiency improvement) to the 24 watt savings (from eliminating the shadow mask), the net saving is 55 watts. That is approximately 44% improved energy efficiency. If all CRTs used this technology, this would reduce US yearly energy consumption by 0.20 quads (end use). We will conservatively use 25% energy savings as a goal. This amounts to 0.10 quad savings. This corresponds to 51 million barrels of oil/year (end use).

Any discussion of energy consumption needs also to consider the embodied energy of the materials used in the device. For this invention, the basic relevant material change in going from magnetic deflection to electrostatic deflection is to add deflection plates (calculated to use 10 gm of stainless steel) and then subtract the material in the external yoke (ignoring here the additional benefit of eliminating the shadow mask embodied energy). The yoke consists of 0.2 to 0.8 lbs. of ferrite and 0.3 lbs. of copper wire (Sanyo Electronics). Copper and stainless steel each have embodied energy of >100 MJ/kg (United Nations data 1990). Ignoring the contribution of the ferrite, changing from .3 lbs. of copper wire to 10 gm of stainless steel provides an embodied energy advantage to electrostatic deflection of 13 MJ per CRT.

Responding to intense criticism at the 1997 Kyoto conference from underdeveloped countries for producing more than our fair share of greenhouse gases, the United States reluctantly committed to an aggressive reduction. This commitment is now being reconsidered by the current administration. However greenhouse gas emission was to be reduced 7% from the 1990 base by 2008 - 2012. Under the management of Office of Industrial Technologies (Dept. of Energy), much effort is underway in major energy consuming industries that consume 80% of the 22.4 Quads manufacturing energy (end use basis) used in this country.

Better efficiencies in these major industries are sure to have an impact. But these are just the obvious big targets. Energy inefficiency is a pervasive problem. Other significant opportunities to reduce energy consumption may exist and need to be studied. We need to examine all commonly used items that consume energy and consider improvements wherever possible. One such major target is the ubiquitous CRT.

Realistically, few people would purchase a new display just because it saves a few dollars in energy costs. However, no one needs to be convinced why they need an inexpensive, higher resolution, smaller footprint display for their new television or computer monitor.

4. CHROMATIC ABERRATIONS AND CRT FOOTPRINT

An ambitious major innovation in CRT technology is planned. Many aspects of electron optics, CRT engineering and manufacturability need to be considered to be reasonably confident that we are not trading one problem that we know of for other problems that we have not yet thought of. Perhaps the most likely technical hazard to the successful completion of this project is the limitation due to chromatic aberrations. That is because electrostatic components are known to have relatively high chromatic aberrations. [13] This needs to be considered in a proposed practical product design.

The plan is to simultaneously solve several problems that are all linked and fortunately have a common solution. The several problems are 1) the high chromatic aberration of electrostatic deflection, 2) the large CRT footprint, 3) the need to dynamically shift the beam slightly to optimally inject it into the scanning deflection plate gap in synchrony with horizontal scan left and right, and 4) the most efficient producers of copious electrons are hot cathodes - but hot cathodes produce a large spread of electron energy (proportional to kT).

For room temperature of 300 degrees Kelvin, kT is approximately 0.02 electron volts. For indirectly heated oxide coated cathodes (1100 degrees Kelvin), which are normally used in television tubes, the energy spread has a mean value of 0.1 electron volt. For directly heated tungsten filaments (2500 degrees Kelvin), the energy spread mean is 0.2 volts. This energy spread can result in an appreciable chromatic aberration that limits performance for many applications.

It is not difficult to estimate the importance of these thermal energies in a CRT. The thermal energy is randomly oriented and necessarily has transverse and longitudinal components. The transverse component is most troublesome. For example, a 20 kV beam is deflected 10 inches over a throw of 12 inches. Ignoring small relativistic effects at this voltage, the velocity of an electron is proportional to the square root of the energy of the electron. The angular spread of the 20,000 volt beam due to a transverse energy of 0.1 electron volt is therefore (0.1/20,000)**0.5 or 0.0022 radians. This angular spread projects to 0.027 inches after 12 inches of throw. Even if all other aberrations were completely eliminated, the thermal spread would cause spot blur on the order of 0.027 inches. Despite the fact that hotter cathodes are more copious and efficient emitters of electrons this calculation shows why in critical applications low temperature electron sources are often used.[13]

In the above example, 0.1 volts added to 20,000 volts along the direction of the gun axis (longitudinal component of thermal energy) adds an insignificant 0.00002 inches to the spot size. This shows that correcting chromatic aberrations would be advantageous once deflection aberrations are reduced in a high-resolution electron optics system. Equally useful would be a way to filter out the low and high energy electrons from the beam. That would tend to make the electron optical system independent of chromatic aberrations.

The solution we are considering is to orient the electron gun sideways or below the CRT rather than protruding out the back as is traditional. Then, using the electrostatic deflection technology, deflect the beam in several steps by 90 degrees or more before it is eventually injected into the scanning system. An aperture is strategically placed in the beam path before the last deflection to intercept the low and high energy components of the beam, passing a more monochromatic beam to the scanning system. This scheme simultaneously causes a smaller footprint CRT (by several inches), solves the chromatic aberration problem, dynamically optimizes beam injection offset (to left side of center for scan left, to right of center to scan right) and allows use of a copious, efficient emitter of electrons.

The two major limitations of CRT displays compared to flat panel displays are excessive footprint and high weight. We can use this deflection technology invention to markedly reduce the footprint of CRTs. Reducing CRT dimensions by bending the beam is not a new idea[14] but by additionally using the reduced deflection aberration invention, the beam may still be as finely focused as if the gun were protruding out the back of the CRT.

By using folded optics, both CRT footprint and chromatic aberrations can be reduced by deflecting the beam first, passing it through a trimming aperture and then scanning. Thus high temperature cathodes can be used and the gun need not protrude out the back of the CRT. Another advantage of using folded electron optics is that guns with large distance from crossover to focus lens (to reduce optical magnification of the crossover) could be used without necessarily increasing the footprint. It appears that brightness and/or resolution can be improved if deflection aberrations can be reduced because of the interdependence of these with other factors that contribute to focused spot size.

5. WILL THE CRT BE AROUND LONG ENOUGH TO JUSTIFY THIS WORK?

Will the CRT be around long enough to justify a major effort to reduce energy? The competition for the CRT is the flat panel. The CRT has several advantages and disadvantages compared to the flat panel. The main advantage is cost in which there is a 5-10 fold advantage of the CRT. According to Castellano, if there were only a 15% cost premium, the flat panel would take the entire display market.[15] The other advantage of the CRT is performance although that is rapidly diminishing as the performance of new flat panels improves. The disadvantages of the CRT are the large horizontal surface area that the device occupies (footprint) and its high weight. What about costs? Consider these 1999 comments by a flat panel marketing committee: 1) due to its low cost "that old CRT refuses to go away". 2) "cathode ray tubes invented 100 years ago will continue to dominate the market at least through the year 2004." 3) "It's price, price, price, price, price and price.", 4) "There were plenty of people in our industry who were overbullish about flat panel displays, but they're not even close to taking over the market", 5) CRTs were supposed to be close to obsolete by 2000. "That year keeps going further and further into the future"[16]

There are 200 million CRTs made annually in the world mainly for the television and computer monitor markets. This is a $22 billion market and growing at 4% per year. The widely predicted replacement of CRTs with flat panels is not happening. It may occur in the future but for now the CRT market remains strong. It is now fully appreciated that the 5-fold cost advantage of the CRT is an important marketing barrier to more expensive displays that only offer a smaller footprint. Flat panel marketing committees suggest that "bragging rights" are not sufficient to overcome major cost disadvantages. At this time, the CRT is the cost-effective solution to many display applications. It may never be displaced in cost sensitive market segments especially if there are significant reductions in footprint.

6. THE EXPERIMENTAL SETUP

A versatile test bed to experimentally determine if the innovation works is currently under construction and is shown in fig.3. It is being built inside a 6-way cross vacuum chamber composed of 10" OD diameter cylinders welded together. An electron gun is situated on one arm (left front) aiming toward a phosphor coated 1" thick glass plate at the opposite arm (right rear). For mechanical alignment of the beam, the electron gun is attached to a bellows (with a glass section to allow the gun flange to float at high voltage if needed) that is attached to the cross. In the figure, the z-axis is along the gun axis from left front to right rear. The y-axis is vertical. The x-axis is in the horizontal plane from left rear to right front. Various size beam-defining apertures are mounted on a stage that is movable in x and y dimensions transverse to the nominal beam z-axis using external mechanical motions. The deflection assembly stage is movable in the x-direction. The beam is deflected in the positive or negative x-direction by the shaped plates that are barely visible in fig. 3 as part of the table-like structure in front of the 1" thick glass screen. For experimental versatility there is redundancy in alignment mechanisms. The beam landing is observed with the use of a video microscope that has a long working distance. There is clearance for 60 degrees of beam deflection on either side. The 6-way cross sits on a conventional pumping station with sufficient pumping speed and suitable instrumentation. The device is under construction at Cooke Vacuum Products in Norwalk, CT. The current setup is designed to operate up to 20 kV. The high voltage power supplies are from Ultravolt, Inc. in Ronkonkama, NY.

We expect to be in initial stages of operation in late summer 2001. The experiment is scheduled for completion by end of 2001. At that time, we will know if the innovation works. We will additionally have knowledge of how large a beam diameter in the deflection plane can be deflected into how large an angle without focus being impaired by deflection aberrations. It is also expected that some understanding of allowable mechanical tolerances will be known. Obviously that is important if and when this invention goes into product design and eventual manufacturing phases.

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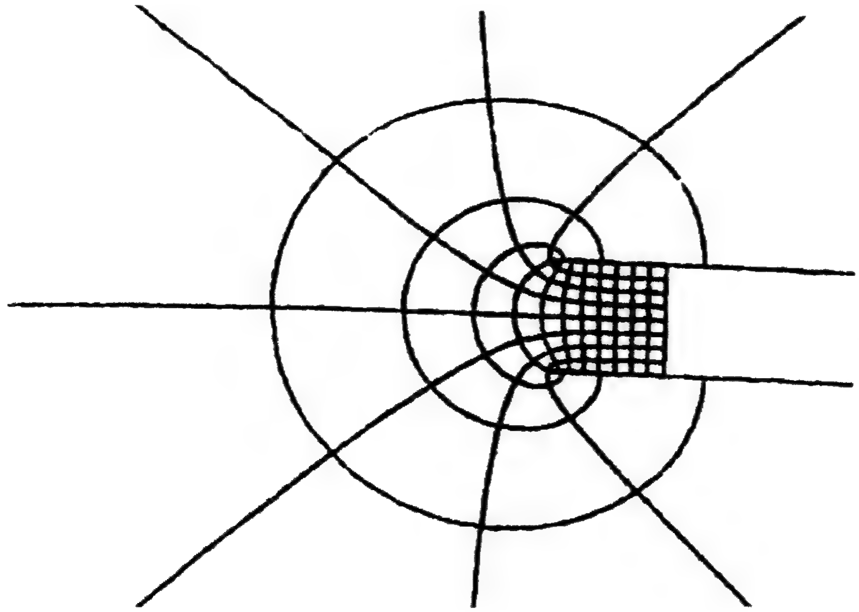

Fig. 1. Equipotentials and lines of force at the edge of a two oppositely charged parallel plates.

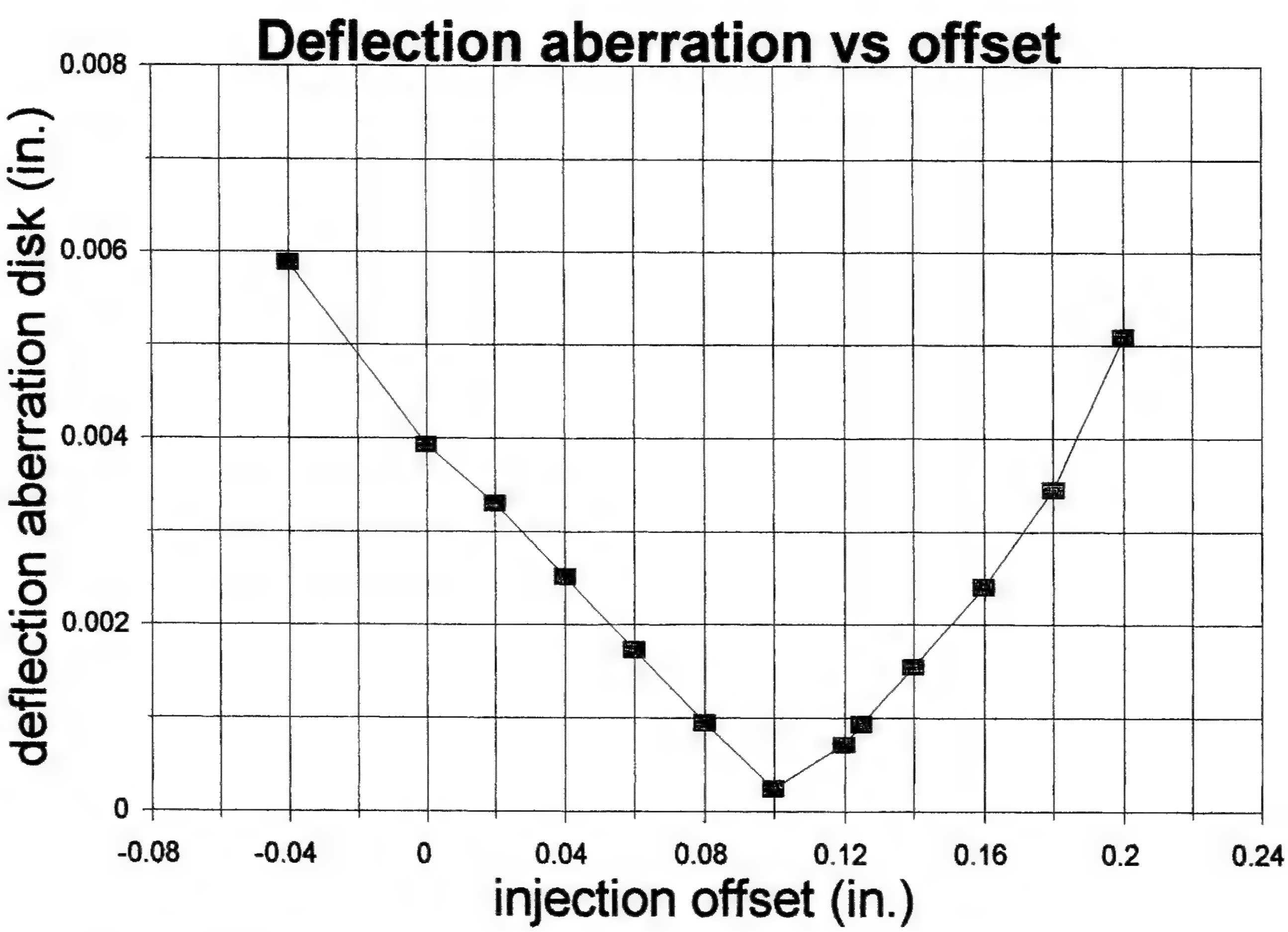

Fig. 2. Output of a computer ray trace program that computes the aberrations due to deflecting an electron beam. The independent variable is the offset from the axis of symmetry to which the beam is directed. It is seen that the optimum injection offset is not in the center as might be suggested from examining fig. 1 above. Rather the optimum is offset toward the attracting plate by approximately 33% in this example.

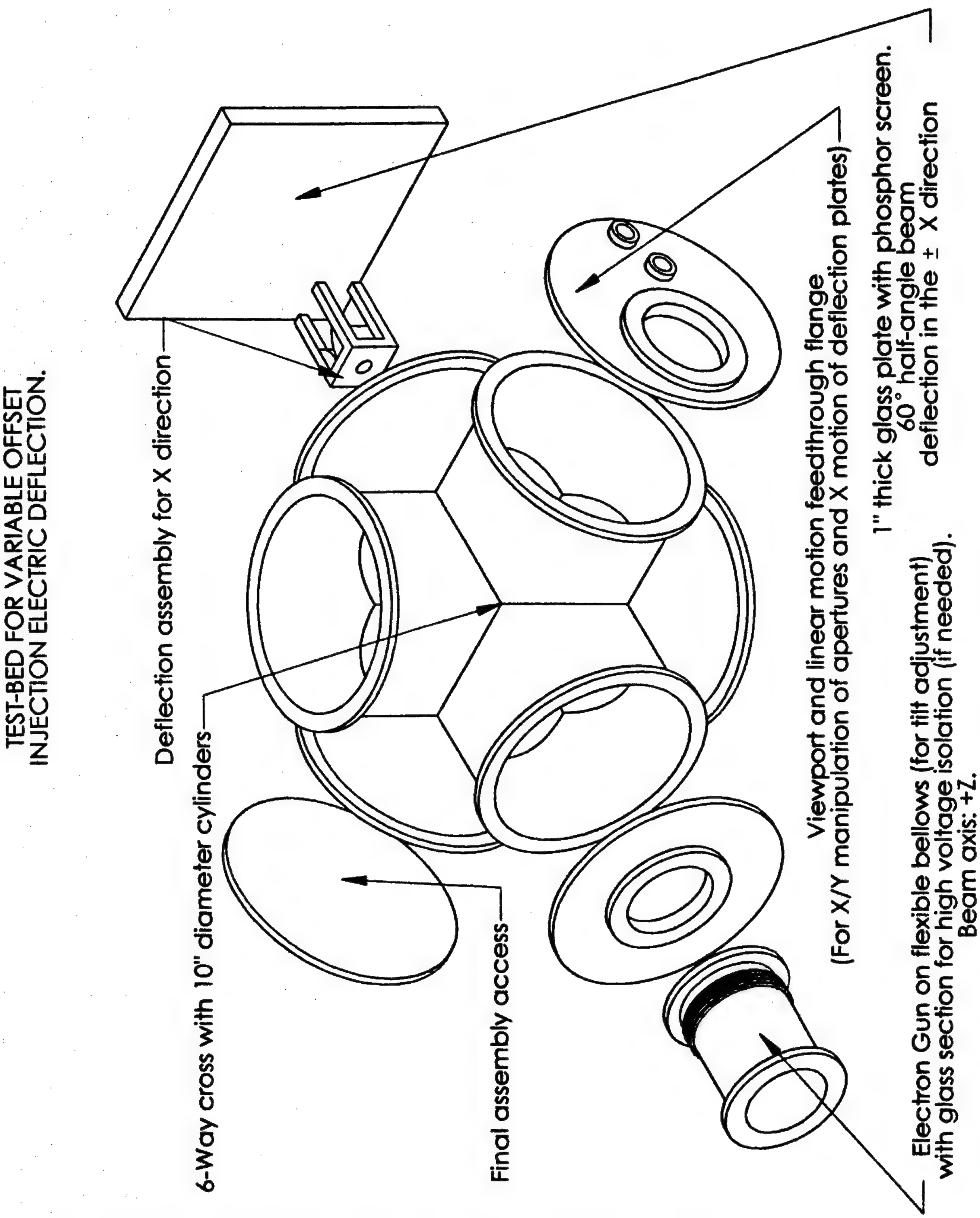

Fig. 3. Test bed for experimental verification of offset injection electric field deflection.

Testing an Electrostatic Deflection Innovatio

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Introduction

Since the Braun tube was first developed over one hundred years ago, many devices and instruments have been built that make use of charged particle beams. In most of these applications, deflecting the beam is essential to the operation of the instrument. Beyond ten or so degrees of deflection, magnetic deflection is normally the choice for deflecting beams since the deflection aberrations are 2-3 times smaller than electric field deflection aberrations (1-3). Since deflection aberrations increase with deflection angle and beam diameter, a variety of detrimental aspects of optical devices such as large system dimensions, low beam current and excessive coulomb repulsion sometimes can be traceable to compromises resulting from deflection aberrations. Improvements in electrostatic deflection have been proposed over the years but a general solution has not been identified (4-6).

Using a custom ray trace program, we proposed a solution that involves injecting the beam offset between two oppositely charged deflection plates. According to this idea, injecting a beam offset 33% or 42% (depending on the method of calculation) of the distance toward the attracting plate will reduce deflection aberrations 10 fold, i.e., to below what is achievable for magnetic deflection (7-9). We built a demountable test-bed to evaluate this concept (10). Initial experimental results are now available.

Results

The system is shown schematically in fig. 1 and in photographs 2a, 2b and 2c. A 6 kV beam 0.010" in diameter is used as a probe. The beam is deflected ± 28.2 degrees by passing it between 2 shaped plates with ± 2.3 kV applied. The plates are 1" long, 0.600" apart at the entrance and flared to 1.4" at the exit. The plates are movable transverse to the nominal beam axis. Thus, injection offset variation is accomplished by moving the plates rather than by moving the injected beam. Beam deflection on a phosphor screen 4.5" from the plate exit vs. beam injection offset is shown in fig. 3 and fig. 4. The center of the plate gap is at 0.6" and the plate gap extends from 0.3" to 0.9" on the horizontal scale in figs. 3 & 4. The phosphor screen and the scale with which beam landing is measured to produce figs. 3 & 4 are stationary.

Fig. 3 is the result of deflecting the beam to the left as viewed from facing the screen. The polarity of the plates is then reversed to provide data for fig. 4. Thus the experiment is repeated by switching attracting plates without letting the system up to air.

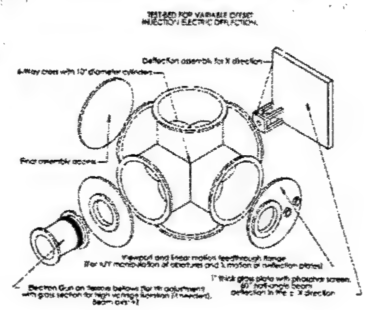


Fig 1. Schematic of the test-bed to measure electrostatic deflection aberrations as a function of beam injection offset.

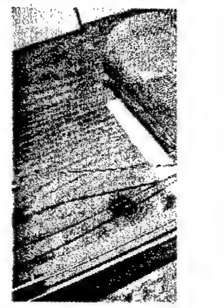


Fig. 2b. Same as fig. screen is added. The fields due to bare wire access port to the defl

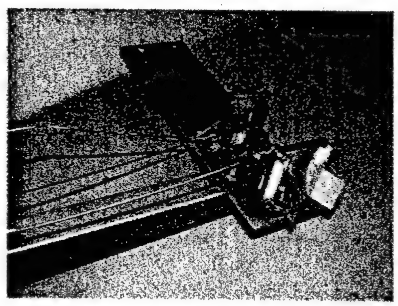
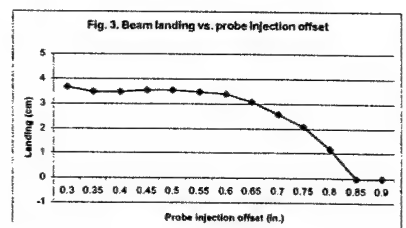


Fig 2a. Assembly showing the movable aperture and movable deflection plates. The beam axis is +z direction (down and to the right in this view). The aperture is movable in x and y directions. The two stages are visible. The plates are movable in the x direction. This stage is also visible. The tab on the near plate is used to attach the deflection high voltage.

Fig. 2c. The assemblec way cross of 10" diame is on the far left. Motio tion plates are on the r supporting the apertur is welded to this ne feedthroughs for the d flange. The 1" thick gl The phosphor screen through the 1" glass pl uum system adjacent t parallax measurement ed on a track that is us seen on the right. The r is used for final assem



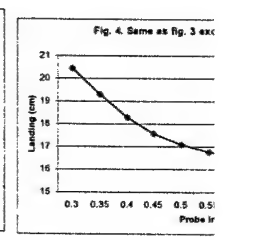


Fig. 3 and 4. Initial data from the demountable. A 0.010" diameter electron beam pro positions into the gap between two oppositely charged conductive plates. The plate the entrance where the gap is smallest. On the horizontal scale in both figs. 3 and 4, t so the probe can be injected from 0.3" to 0.9". The positive (attracting) plate is at 0. In each figure, there is a window approximately 0.2" wide and centered 0.1" from attracting plate where the beam landing vs. injection offset is flat. In other words, a pa ment will exit parallel. This indicates a segment where the deflection aberrations are er than at the point of symmetry

Acknowledgement: This work was supported by 1) SBIR Phase I grant (1R43CA90150-01) NIH, NCI, 2) Department of the Army (grant award DAMD17-01-1-0518), 3) an Inventions and Innovations grant from Department of Energy (GO11021), of Connecticut. This publication is solely the responsibility of the author and does not necessarily represent the official views of the Government and no official endorsement should be inferred.

static Deflection Innovation: Initial Experimental Re

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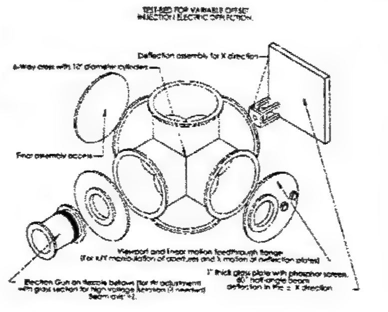

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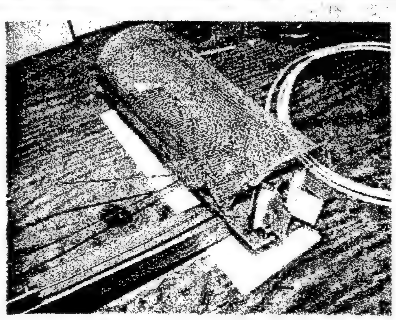
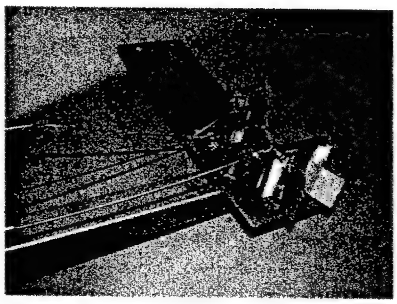


Fig. 2b. Same as fig. 2a but a grounded metallic screen is added. The screen shields the beam from fields due to bare wire high voltage leads from the top access port to the deflection plates.



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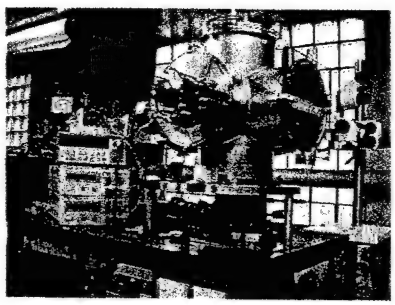
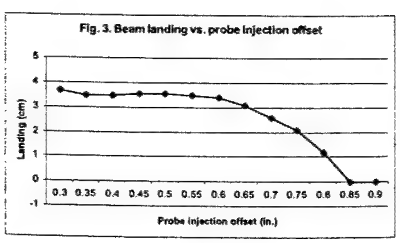


Fig. 2c. The assembled test-bed. It is built inside a 6-way cross of 10" diameter cylinders. The electron gun is on the far left. Motions for the aperture and deflection plates are on the near left flange. The square bar supporting the aperture and plates in figs. 2a and 2b is welded to this near left flange. High voltage feedthroughs for the deflection plates are on the top flange. The 1" thick glass plate is on the right flange. The phosphor screen and glass scale are visible through the 1" glass plate. The scale is within the vacuum system adjacent to the phosphor screen to avoid parallax measurement errors. The microscope mounted on a track that is used to measure beam landing is seen on the right. The rear flange not seen in this view is used for final assembly. The pumps are below.



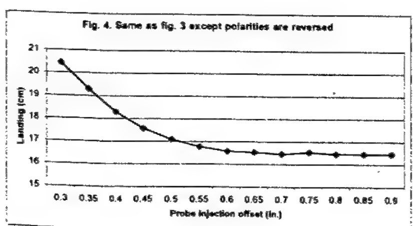


Fig. 3 and 4. Initial data from the demountable. A 0.010" diameter electron beam probe is injected at various offset positions into the gap between two oppositely charged conductive plates. The plates are 1" long and 0.6" apart at the entrance where the gap is smallest. On the horizontal scale in both figs. 3 and 4, the symmetrical center is at 0.6" so the probe can be injected from 0.3" to 0.9". The positive (attracting) plate is at 0.3" in fig. 3 and at 0.9" in fig. 4. In each figure, there is a window approximately 0.2" wide and centered 0.1" from geometrical center toward the attracting plate where the beam landing vs. injection offset is flat. In other words, a parallel beam injected in this segment will exit parallel. This indicates a segment where the deflection aberrations are at a minimum and clearly smaller than at the point of symmetry

Conclusions

It can be seen that deflection aberrations ar
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Figure 4 rotated by 180 degrees is very similar to fig. 3. This shows that the effect is reproducible and not the result of random dust or contamination on one or the other plate.

With symmetrical injection, electrostatic deflection aberrations occur because the parts of the beam that are far from the attracting plate are deflected more than corresponding parts of the beam that are near the attracting plate. Deflection increases quadratically as the distance from the attracting plate increases past the plane of symmetry. This explains why electrostatic deflection shows some focusing action in the plane of deflection and also why a quadrupole cancels some but not all of the aberration.

The data reported here support the theoretical prediction. Furthermore, there is no apparent reason why this technique cannot provide ±45 to ±55 degrees of deflection with little or no deflection aberrations.

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3

Testing an electrostatic deflection innovation: Initial experimental results

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(Received 28 May 2002; accepted 30 September 2002)

When deflecting a charged particle beam into small angles, electrostatic deflection is commonly used. For larger angles, magnetic is the usual choice mainly because the deflection aberrations are two- or threefold less. Methods to reduce electrostatic deflection aberrations have been proposed over the years but a major solution has not been identified. This subject has recently been revisited and, based on computations, it has been proposed that electrostatic deflection aberrations can be reduced 10-fold if the beam is injected asymmetrically into the gap between two conventional shaped oppositely charged conducting plates. According to this theory, with the proper injection offset, the only surviving aberration is astigmatism that is totally correctable with a quadrupole prior to deflection. The predicted optimal offset was either 33% or 42% (depending on the method of calculation) from the center toward the attracting plate. We have built a demountable test bed to experimentally determine if the innovation is correct. The beam is deflected by shaped plates according to a previously reported design. This plate design was predicted to provide $\pm 38.1°$ of deflection for a beam 0.050 in. in diameter with undetectable deflection aberrations at optimal offsets. Compared to the calculated design, the voltages used in the demountable test bed are smaller (6 compared to 20 kV), the throw distance from the plate entrance to the screen is smaller (4.5 compared to 12 in.), and the deflection angle is $\pm 28.2°$ but otherwise the setups are very similar. Initial data from the test bed are deflection of a 0.010 in. diam probe after injection into the deflection plate gap at various offset positions. It is found that 1/3 of the way from center toward the attracting plate, there is a 0.2 in. wide section of the deflection versus offset curve that is flat indicating a segment in which the aberrations are not detectable. Based on these initial results, the concept is valid and the injection offset was where it was predicted to be. [DOI: 10.1116/1.1523020]

I. INTRODUCTION

Since the cathode ray tube was first developed over 100 years ago, many devices and instruments have been built that make use of charged particle beams. In most of these applications, deflecting the beam is essential to the operation of the instrument. There are two ways to deflect beams—passing them transversely through either magnetic or electric fields. Electric fields are simpler to produce and consume less power. Beyond 10° or so of deflection, the magnetic field is normally the choice since the deflection aberrations are two to three times smaller than electric field deflection aberrations.[1–3] Since deflection aberrations increase with the deflection angle and beam diameter, a variety of detrimental aspects of optical devices such as large system dimensions, low beam current and excessive Coulomb repulsion sometimes can be traceable to compromises resulting from deflection aberrations. Improvements in electrostatic deflection have been proposed over the years but a general solution has not been identified.[4–6]

Using a custom ray trace program,[7] we proposed a solution that involves injecting the beam offset between two oppositely charged deflection plates. According to this idea, injecting a beam offset 33% or 42% (depending on the method of calculation) of the distance toward the attracting plate will reduce deflection aberrations 10-fold, i.e., to below what is achievable for magnetic deflection.[8–10] This is counterintuitive, at least judging by the fringe fields as seen in Fig. 1. It would seem logical to avoid these fringe fields as much as possible by injecting the beam centered between the two plates.

However, from another perspective, an asymmetrical solution may not be so unreasonable. In Feynman's famous 1959 talk to the American Physical Society at Caltech when nanotechnology was first discussed, he lamented on the limitation in resolution of electron microscopes: "The reason the electron microscope is so poor is that the *f* value of the lenses is only 1 part to 1000; you do not have a big enough numerical aperture. And I know there are theorems which prove that it is impossible, with axially symmetrical stationary field lenses, to produce an *f* value any bigger than so and so; and therefore the resolving power at the present time is at its theoretical maximum. But in every theorem there are assumptions. Why must the field by symmetrical? I put this out as a challenge: Is there no way to make the electron microscope more powerful?."[11]

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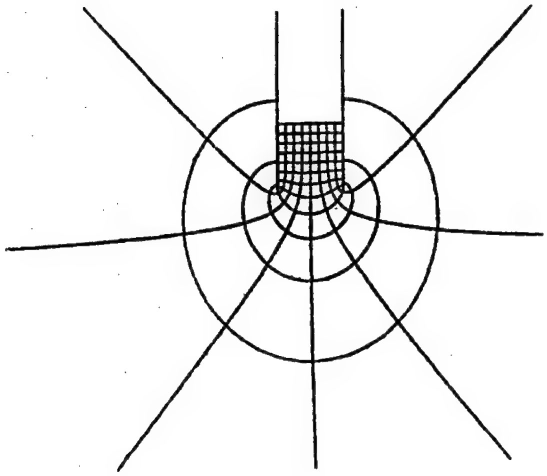


FIG. 1. Equipotentials and lines of force at the edge of two oppositely charged parallel plates. Traditionally, when deflecting charged particle beams, the particles are injected centered between the plates to avoid the fringe field as much as possible.

We built a demountable test bed to evaluate the asymmetrical injection concept.[12] Initial experimental results are now available.

II. RESULTS

The system is shown schematically in Fig. 2 and in photographs in Figs. 3(a) and 3(b). A 6 kV beam 0.010 in. in diameter is used as a probe. While the cathode is a bare tungsten filament with a typical 0.2 eV thermal spread, the 0.010 in. aperture is approximately 20 in. away producing a calculated 0.002 eV transverse energy spread in the beam that enters the deflection assembly. As a result, chromatic aberrations have not been noticeable as contributing to deflection aberrations. [The separate effects of longitudinal and transverse energy spread in the beam were discussed for cathode ray tube (CRT) applications previously.[12]] The beam is deflected ±28.2° by passing it between two shaped plates with ±2.3 kV applied. The plates are 1 in. long, 0.600 in. apart at the entrance and flared to 1.4 in. at the exit. The plates are movable transverse to the nominal beam axis. Thus, variation in injection offset is accomplished by moving the plates rather than by moving the injected beam. Beam deflection on a phosphor screen 4.5 in. from the plate entrance versus the beam injection offset is shown in Figs. 4 and 5. The center of the plate gap is at 0.6 in. and the plate gap extends from 0.3 to 0.9 in. on the horizontal scale in Figs. 4 and 5. The phosphor screen and the scale with which beam landing is measured to produce Figs. 4 and 5 are stationary.

Figure 4 is the result of deflecting the beam to the left viewed facing the screen. The polarity of the plates is then reversed to provide the data for Fig. 5. Thus the experiment is repeated by switching attracting plates without letting the system up to air. Figure 5 data from 0.3 to 0.6 in. fit a quadratic form with $r^2=0.999$.

III. CONCLUSIONS

It can be seen that deflection aberrations are far smaller toward the attracting plate in both Figs. 4 and 5. In fact, there is an offset segment approximately 0.2 in. in size (or 1/3 of the entire gap) in both Figs. 4 and 5 where the beam deflection is independent of the injection offset. That is, any electron in a parallel beam injected into the gap between the plates in that segment will be deflected by the same amount. Or, if a round parallel beam were injected in that segment, it

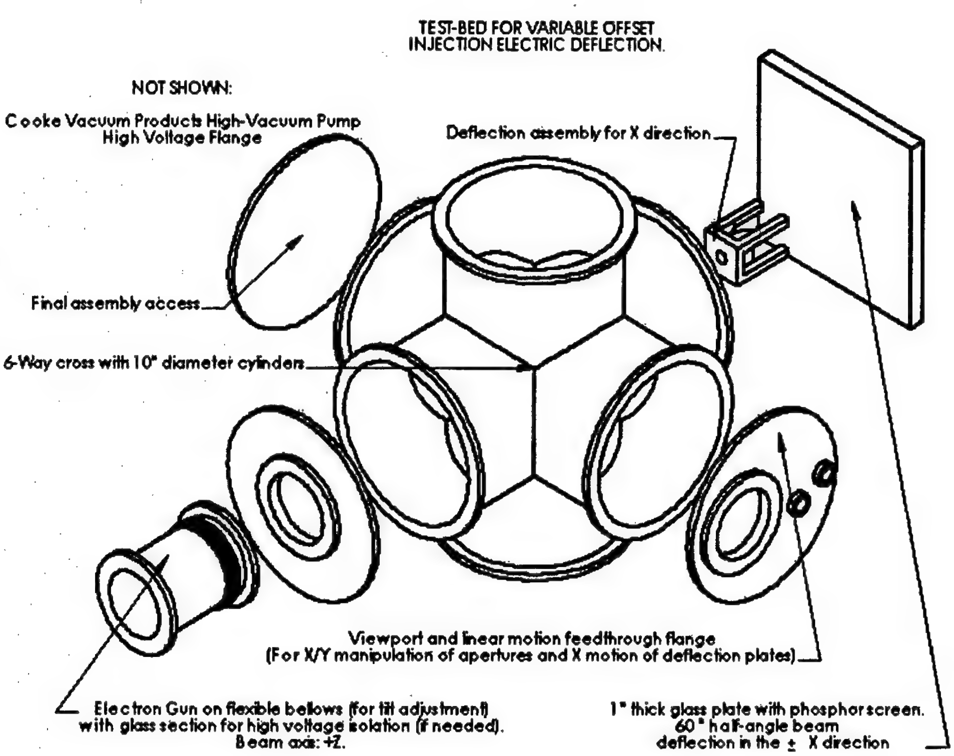
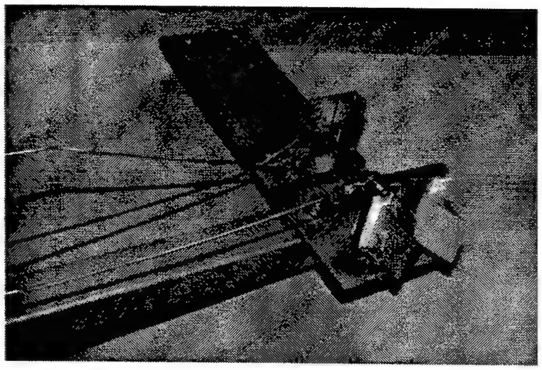


FIG. 2. Schematic of the test bed that can measure electrostatic deflection aberrations as a function of the beam injection offset.



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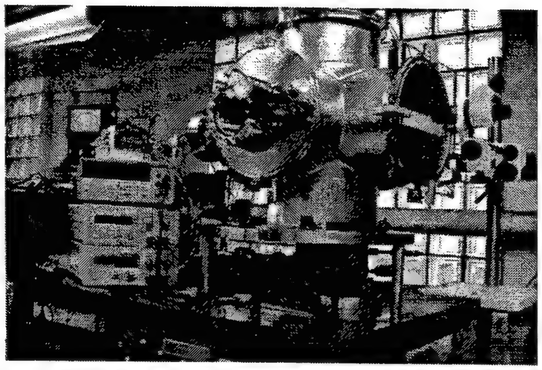

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FIG. 3. (a) Assembly showing the movable aperture and movable deflection plates. The beam axis is the $+z$ direction (down and to the right in this view). The aperture is movable in the x and y directions. The two stages are visible. The plates are movable in the x direction. This stage is also visible. The tab on the nearer plate is used to attach the deflection high voltage. A grounded metallic screen, not shown, shields the beam from fields due to bare wire high voltage leads from the top access port to the deflection plates. (b) Assembled test bed. It is built inside a six-way cross of 10 in. diam cylinders. An electron gun is on the far left. Motion for the aperture and deflection plates is on the near left flange. The square bar supporting the aperture and plates in (a) is welded to this near left flange. High voltage feedthroughs for the deflection plates are on the top flange. The 1 in. thick glass plate is on the right flange. The phosphor screen and glass scale are visible through the 1 in. glass plate. The scale is within the vacuum system adjacent to the phosphor screen to avoid parallax measurement errors. The microscope mounted on a track that is used to measure the beam landing is seen on the right. The rear flange, not seen in this view, is used for final assembly. The pumps are below.

would emerge also round and parallel. The aberrations in this segment are too small to measure with our technique. There is no equivalent segment on the half of the gap closest to the repelling plate in either Fig. 4 or 5. The center of beam placement for minimum deflection aberrations is approximately 1/3 the distance from the center to the attracting plate, where it was predicted to be.

Figure 5 rotated 180° is very similar to Fig. 4. This shows that the effect is reproducible and not the result of random dust or contamination on one or the other plate.

With symmetrical injection, the nature of electrostatic deflection aberrations is now clear. Since deflection is uniform on the attracting side of the beam but increases quadratically with distance from the center on the repelling side, half of the beam will tend to fold over onto itself. This explains why

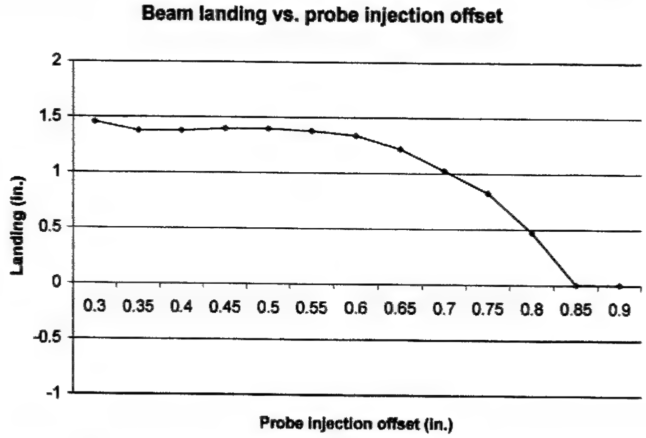

FIG. 4. Initial data from the demountable test bed. A 0.010 in. diam electron beam probe is injected at various offset positions into the gap between two oppositely charged conductive plates. The plates are 1 in. long and 0.6 in. apart at the entrance where the gap is smallest. On the horizontal scale, the symmetrical center is at 0.6 in. so the probe can be injected from 0.3 to 0.9 in. The positive (attracting) plate is at 0.3 in. There is a window approximately 0.2 in. wide that is centered 0.1 in. from the geometrical center toward the attracting plate where the beam landing vs injection offset is flat. In other words, a parallel beam injected in this segment will exit parallel. This indicates a segment where the deflection aberrations are at a minimum and clearly smaller than at the point of symmetry.

electrostatic deflection shows partial focusing action in the plane of deflection. This action is somewhat quadrupole like, explaining why a stigmator cancels some but not all of the aberration as reported by Kanaya and Baba.[6] While the aberration can be mathematically described in only a few sentences, it would appear to be very difficult if not impossible for any external field configuration of electric and/or magnetic fields to correct the aberration. This explains why empirical approaches have not solved this problem.

Traditional theoretical approaches to the study of electrostatic deflection aberrations neglect details of the structure of fringe fields presumably since they are complex (as shown in Fig. 1) and not expressible in closed form. In the way treated

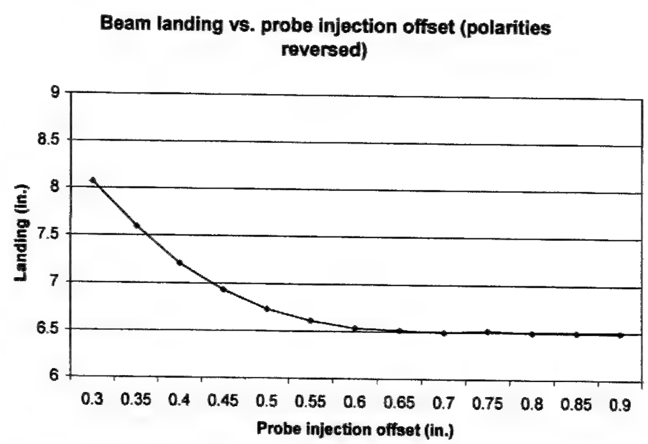

FIG. 5. Initial data from the demountable test bed. A 0.010 in. diam electron beam probe is injected at various offset positions into the gap between two oppositely changed conductive plates. The plates are 1 in. long and 0.6 in. apart at the entrance where the gap is smallest. The positive (attracting) plate is at 0.9 in.

by Szilagyi,[13] for example, the fringe field is approximated by merely assuming that the effective plate length is truncated by a geometric factor compared to the physical length because the field drops off inside the plate towards the edge. Then, rays are studied using paraxial approximations that involve polynomial expansions about the axis of symmetry. The solutions we have found that are 33%–42% from symmetry towards the boundary are too far off axis to be studied with paraxial ray approximations. From our results, details of the structure of the fringe field pattern cannot be ignored and the solutions are not paraxial. This explains why previous analytical approaches have not found the solution that we have reported.

In retrospect, there may be two intuitive explanations of why offset injection should be an improvement. First, a beam injected centered will exit off center with a deflecting field applied. Therefore it is not logical to automatically assume that the optimal injection point is on center. Second, the optimally injected rays more or less follow equipotentials as they pass through the plates. Since they form an orthonormal set, lines of force are perpendicular to equipotentials. Thus as the electrons travel toward the target, deflection forces are always perpendicular to the direction of travel. Perhaps that is the ultimate source of the advantage that we report here.

A simple far-off-axis solution seems to produce a major improvement in this commonly used electron optical device. Perhaps there are other situations in electron optics where long-standing approaches need to be reexamined by other than paraxial ray approximations and symmetrical field techniques.

The data reported here support our theoretical prediction. Furthermore, there is no apparent reason why this technique cannot provide $\pm 45-\pm 55°$ of deflection with little or no deflection aberration.

Some deflection system designs such as our test example apparently do not need an astigmatism correcting quadrupole.

We are currently investigating applications of this technology in other areas including electron beam lithography. Since electron sources such as thermal-field emitters with approximately 1 eV beam energy spread are used in lithography, this will need to be considered as well as the requirement to provide 50 nm resolution over a large area.

ACKNOWLEDGMENTS

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New High Resolution Display For

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Abstract

According to the National Institutes of Health, digital mammography is one of the most promising research areas for improving early detection of breast cancer. However, the limitations of current display systems remain an impediment to full realization of its potential.

We have been studying how to improve the resolution of inexpensive cathode ray tubes (CRTs) so that they can meet what has been available from x-ray film. In a cathode ray tube display, an electron beam is scanned in raster fashion over a phosphor screen. The current in the beam is modulated to produce the desired light output pattern. Because of the low mass of electrons it is easy to deflect electron beams. It is much harder to additionally preserve the ability to finely focus the beam after deflection. There are two ways to deflect an electron beam - using magnetic fields or electric fields. The vast majority of CRT displays use magnetic deflection. The basic advantage of magnetic deflection is that deflection aberrations are lower. A way to significantly reduce electric field deflection aberrations would be an important development.

This has recently been accomplished – initially according to calculations and now verified by experimental results. We intend to prototype an 8 megapixel, 300 microamp beam current CRT with electric field deflection. This will be an improvement over what is currently available from any CRT. Using this display in digital mammography workstations will likely help radiologists identify malignancies and ignore benign lesions.

Introduction

Since the cathode ray tube was first developed over one hundred years ago, many devices and instruments have been built that make use of charged particle beams. In most of these applications, deflecting the beam is essential to the operation of the instrument. There are two ways to deflect beams – passing them transversely through either magnetic or electric fields. Electric fields are simpler to produce and consume less power. Beyond ten or so degrees of deflection, magnetic field is normally the choice since the deflection aberrations are 2-3 times smaller than electric field deflection aberrations (1-3). Since deflection aberrations increase with deflection angle and beam diameter, a variety of detrimental aspects of optical devices such as large system dimensions, low beam current and excessive coulomb repulsion sometimes can be traceable to compromises resulting from deflection aberrations. Improvements in electrostatic deflection have been proposed over the years but a general solution has not been identified (4-6).

Using a custom ray trace program, we proposed a solution that involves injecting the beam offset between two oppositely charged deflection plates (US Patents 5,825,123 and 6,232,709). According to this idea, injecting a beam offset 33% or 42% (depending on the method of calculation) of the distance toward the attracting plate will reduce deflection aberrations 10 fold, i.e., to below what is achievable for magnetic deflection (7-9). We built a demountable test-bed to evaluate the asymmetrical injection concept (10,11).

The system is shown schematically in *fig. 1* and in photographs *2a, 2b* and *2c*. A 6 kV beam 0.010" in diameter is used as a probe. The beam is deflected ± 28.2 degrees by passing it between 2 shaped plates with ± 2.3 kV applied. The plates are 1" long, 0.600" apart at the entrance and flared to 1.4" at the exit. Data are shown in *figs. 3* and *4*.

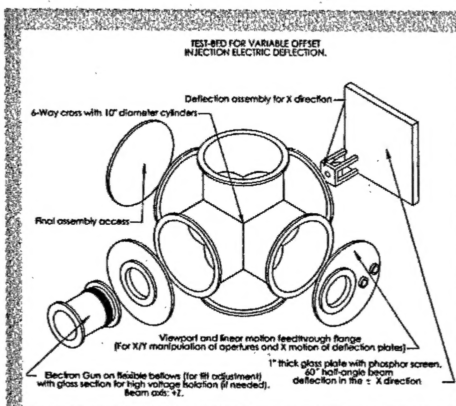

Fig 1. Schematic of the test-bed to measure electrostatic deflection aberrations as a function of beam injection offset.

Fig. 3. Beam landing vs. probe injection offset

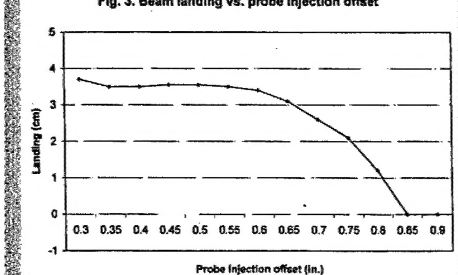

Fig. 4. Same as fig. 3 except polarities are reversed

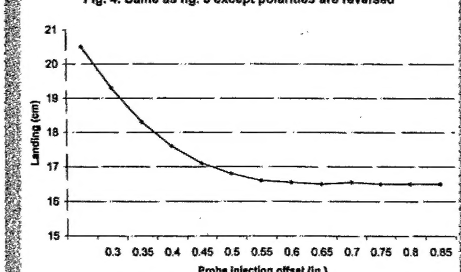

Fig. 3 and 4. Initial data from the demountable. A 0.010" diameter electron beam probe is injected at various offset positions into the gap between two oppositely charged conductive plates. The plates are 1" long and 0.6" apart at the entrance where the gap is smallest. On the horizontal scale in both figs. 3 and 4, the symmetrical center is at 0.6" so the probe can be injected from 0.3" to 0.9". The positive (attracting) plate is at 0.3" in fig. 3 and at 0.9" in fig. 4. In each figure, there is a window approximately 0.2" wide and centered 0.1" from geometrical center toward the attracting plate where the beam landing vs. injection offset is flat. In other words, a parallel beam injected in this segment will exit parallel. This indicates a segment where the deflection aberrations are at a minimum and clearly smaller than at the point of symmetry

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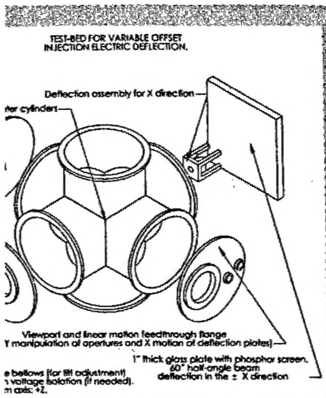

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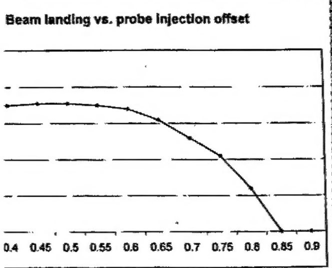

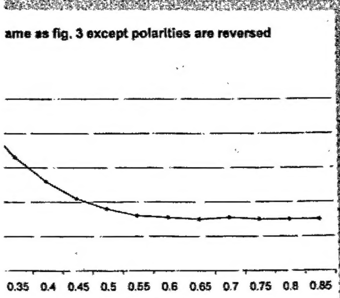

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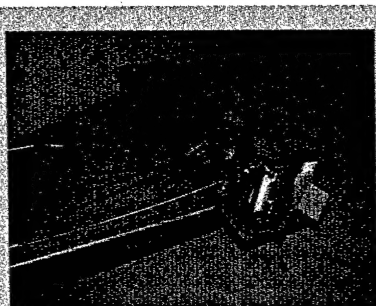

Fig 2a. Assembly showing the movable aperture and movable deflection plates. The beam axis is +z direction (down and to the right in this view). The aperture is movable in x and y directions. The two stages are visible. The plates are movable in the x direction. This stage is also visible. The tab on the near plate is used to attach the deflection high voltage.

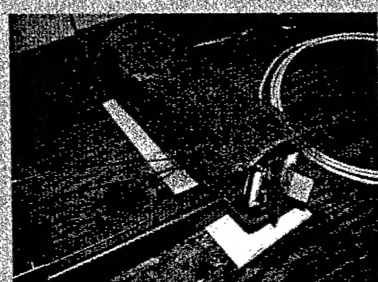

Fig. 2b. Same as fig. 2a but a grounded metallic screen is added. The screen shields the beam from fields due to bare wire high voltage leads from the top access port to the deflection plates.

Fig. 2c. The assembled test-bed. It is built inside a 6-way cross of 10" diameter cylinders. The electron gun is on the far left. Motions for the aperture and deflection plates are on the near left flange. The square bar supporting the aperture and plates in figs. 2a and 2b is welded to this near left flange. High voltage feedthroughs for the deflection plates are on the top flange. The 1" thick glass plate is on the right flange. The phosphor screen and glass scale are visible through the 1" glass plate. The scale is within the vacuum system adja- cent to the phosphor screen to avoid parallax measurement errors. The microscope mounted on a track that is used to measure beam landing is seen on the right. The rear flange not seen in this view is used for final assembly. The pumps are below.

Conclusions

It can be seen that deflection aberrations are far smaller toward the attractir *fig. 4*. In fact, there is an offset segment approximately 0.2" in size (or 1/3 of *fig. 3* and *fig. 4* where the beam deflection is independent of the injection offs a parallel beam injected into the plate gap in that segment will be deflected by round parallel beam were injected in that segment, it would emerge also aberrations in this segment are too small to measure with our technique. There on the half of the gap closest to the repelling plate in either *fig. 3* or *4*. The cen for minimum deflection aberrations is approximately 1/3 of the distance from ' plate - where it was predicted to be. *Figure 4* rotated by 180 degrees is very s that the effect is reproducible and not the result of random dust or contaminatio

These data support our theoretical prediction. Furthermore, there is no apparen cannot provide ±45 to ±55 degrees of deflection with little or no deflection aberr capability to make an improved CRT display for medical imaging and digital m in particular. The CRT will be capable of resolving very fine microcalcificat although that is beyond the present limitations of drive circuitry. A compromise 300 microamp display that is within circuitry capability and an improvement ov

Addenda

Germane to this Era of Hope Conference, the author also studies breast canc Folkman Surgical Research Laboratory at Harvard Medical School (12-14) breast cancer screening controversy has recently been submitted to Current Gynecology for Feb 2003 publication.

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Conclusions

It can be seen that deflection aberrations are far smaller toward the attracting plate in both *fig. 3* and *fig. 4*. In fact, there is an offset segment approximately 0.2" in size (or 1/3 of the entire gap) in each of *fig. 3* and *fig. 4* where the beam deflection is independent of the injection offset. That is, any electron in a parallel beam injected into the plate gap in that segment will be deflected by the same amount. Or if a round parallel beam were injected in that segment, it would emerge also round and parallel. The aberrations in this segment are too small to measure with our technique. There is no equivalent segment on the half of the gap closest to the repelling plate in either *fig. 3* or *4*. The center of the beam placement for minimum deflection aberrations is approximately 1/3 of the distance from the center to the attracting plate - where it was predicted to be. *Figure 4* rotated by 180 degrees is very similar to *fig. 3*. This shows that the effect is reproducible and not the result of random dust or contamination on one or the other plate.

These data support our theoretical prediction. Furthermore, there is no apparent reason why this technique cannot provide ±45 to ±55 degrees of deflection with little or no deflection aberration. We intend to use this capability to make an improved CRT display for medical imaging and digital mammography workstations in particular. The CRT will be capable of resolving very fine microcalcifications similar to x-ray film - although that is beyond the present limitations of drive circuitry. A compromise is to make an 8 megapixel 300 microamp display that is within circuitry capability and an improvement over what is available.

Addenda

Germane to this Era of Hope Conference, the author also studies breast cancer and angiogenesis in the Folkman Surgical Research Laboratory at Harvard Medical School (12-14). An invited review on the breast cancer screening controversy has recently been submitted to Current Opinions in Obstetrics and Gynecology for Feb 2003 publication.

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